Above-soil and in-soil degradation of oxo- and bio-degradable mulches: a qualitative approach

L. Martín-Closas [A,H], *J. Costa* [A], *A. Cirujeda* [B], *J. Aibar* [C], *C. Zaragoza* [B], *A. Pardo* [D], *M. L. Suso* [D], *M. Moreno* [E], *C. Moreno* [F], *I. Lahoz* [G], *J. I. Mácua* [G], *and A. M. Pelacho* [A]

[A]Department of Horticulture, Botany and Gardening, School of Agrifood and Forestry Science and Engineering, University of Lleida, Avenida Alcade Rovira Roure 191, 25198 Lleida, Spain.
[B]Department of Plant Health, CITA (DGA), Apdo. 727, 50080 Zaragoza, Spain.
[C]Department of Agricultural and Environmental Sciences, EPS, University of Zaragoza, Carretera de Cuarte s/n, 22071 Huesca, Spain.
[D]Department of Natural Resources, CIDA, Carretera Mendavia-Logroño km 88, 26071 Logroño, Spain.
[E]Department of Plant Production and Agrarian Technology, School of Agricultural Engineering, University of Castilla-La Mancha, Ronda de Calatrava 7, 13071 Ciudad Real, Spain.
[F]Department of Mathematics, School of Agricultural Engineering, University of Castilla-La Mancha, Ronda de Calatrava 7, 13071 Ciudad Real, Spain.
[G]INTIA, Finca Experimental de Cadreita, Camino Alfaro s/n, 31515 Cadreita, Spain.
[H]Corresponding author. Email: martin@hbj.udl.cat

Abstract. Degradable materials have been suggested to overcome accumulation in the field of persistent plastic residues associated with the increasing use of polyethylene mulches. New degradable materials have been proven successful for increasing crop productivity; however, their degradation in the field has been hardly addressed. A qualitative scale was used in the present study to assess the above-soil and in-soil degradation of degradable mulches during the cropping season. Degradation was determined in three biodegradable plastic mulches (Biofilm, BF; Mater- Bi, MB; Bioflex, BFx), two paper sheet mulches (Saikraft, PSA; MimGreen, PMG) and one oxo-degradable plastic mulch (Enviroplast, EvP). Polyethylene (PE) mulch was used as control. Mulches were tested in five Spanish locations (Castilla-La Mancha, La Rioja, Navarra, Aragón and Catalunya), with three crop seasons of processing tomato. Biodegradable plastic mulches BF and MB degraded more and faster above-soil than paper mulches; among biodegradable mulches BF degraded more than MB, and MB more than BFx. The above-soil degradation of the oxo-degradable mulch EvP was highly dependent on location and crop season, and it degraded more than PE. Main environmental factors triggering above-soil degradation were radiation, rainfall and crop cover. In-soil, paper mulches and BF degraded more and faster than MB, whereas BFx and EvP barely degraded. Environmental factors triggering in-soil degradation during the crop season were rainfall and irrigation water. The effect of soil parameters (organic matter, nutrient availability) on degradation during the cropping season was not evidenced. The qualitative scale used proved convenient for determining mulch field degradation. A visual scale for supporting the qualitative evaluation is provided. In order to standardise parameters and criteria for future studies on field mulching degradation evaluation, a unified degradation qualitative scale is suggested.

Additional keywords: biodegradation, *Lycopersicon esculentum*, oxo-degradation, paper, plastic, qualitative scale.
Received 8 May 2015, accepted 17 November 2015, published online 22 March 2016

Introduction

Plastic mulches were first used in commercial agriculture in the early 1960s. Their use has expanded worldwide and they have increasingly replaced other types of mulches (e.g. paper, straw). The effect of mulching to increase productivity and quality of a wide diversity of crops such as maize, rice, cotton, sugarcane, fruit crops, and mostly vegetables (tomato, muskmelon, watermelon, pepper, eggplant, squash, etc.) is extensively recognised. A comprehensive review on the application of plastic mulches in agriculture can be found in Kasirajan and Ngouajio (2012). The use and benefits of other types of mulches in landscape plants is reviewed in Chalker- Scott (2007). The multiple benefits of this technique include the ability of mulches to improve the thermal environment surrounding the crop, their stabilising effect on the soil-water profile and, for opaque mulches, their control of weed development (Tarara 2000). From an environmental perspective, the positive effect of mulching lies in the enhancement of water and nutrient use efficiency, together with the control of weeds, which avoids herbicide spraying or mechanical weeding. Consequently, although the prevailing mulch materials are synthetic and non-renewable, mostly made out of polyethylene (PE), their use is allowed in organic production systems (European Commission 2013), where they are commonly employed.

Some substantial drawbacks may discourage the use of PE mulches. At the end of the crop cycle, the mulch material remains mostly intact and persists in a soil where it has ceased to be useful. The limited time for which the material is required and its long persistence are at odds (Martín-Closas and Pelacho 2011). The disproportionate stability of the material prevents it from being degraded in the soil; this persistence results in substantial technical inconveniences and it pollutes the environment. All of these facts raise doubts about the sustainability of conventional plastic mulch.

To overcome these shortcomings, the use of materials that meet the agronomic functions required from mulches, and which can be assimilated by the agricultural system at the end of their life cycle, is proposed. The choices are: (*i*) bio-based biodegradable polymers, or mixtures thereof with biodegradable synthetic materials; and (*ii*) polyethylene-based oxo-degradable polymers to which additives are incorporated to accelerate degradation. Some of these materials have been studied from the perspective of the agronomic requirements (Martín-Closas *et al*. 2003; Arméndariz *et al*. 2006; Moreno and Moreno 2008; Cirujeda *et al*. 2012; Li *et al*. 2014*a*). However, studies concerning their degradation in the field, as affected by a range of agro-climatic conditions, are scarce; most studies compare polyethylene to one or a few materials in only one location (Scarascia-Mugnozza *et al*. 2006; Martin-Closas *et al*. 2008; Rudnik and Briassoulis 2011).

Furthermore, on-site methodologies for monitoring mulch degradation in the field are very limited. The evaluation of developed in a similar manner to those usually applied for characterising the phenology of crop cultivars in field trials, severity of diseases in plant leaves or soil erosion (Van Loon et al. 2005). The scale for determining the degradation of mulch materials was soon implemented in field studies (Martín-Closas and Pelacho 2004; Caprara et al. 2006), and from then on it has been routinely used (Martin-Closas et al. 2008; Filippi et al. 2011). Two more specific qualitative scales have since been developed (Shogren and Hochmuth 2004; Miles et al. 2012; Cowan et al. 2013). Nevertheless, although all three scales are routinely used in field studies and they evaluate similar parameters, above-soil and in-soil degradation, they have not been compared and standardised.

By means of the initially designed qualitative scale, the present paper aims at assessing the above-soil and in-soil degradation of commercial biodegradable mulch films in the field during the cropping season, in five agro-climatic conditions. Based on the results obtained and on the analysis of previously existing qualitative scales, a new unified scale for field mulch evaluation is suggested.

Materials and methods

Agro-climatic conditions and crop features

The study was carried out in three crop seasons (2006, 2007 and 2008), and at five locations in Spain: Ciudad Real (Castilla-La Mancha); Valdegón (La Rioja); Cadreita (Navarra); Almudévar (2006, 2007 only) and Montañana (2008 only) (Aragón); and Vilanova de Bellpuig (Catalunya). At Valdegón, Cadreita and Almudérvar–Montañana, integrated crop production techniques were applied; Ciudad Real was in transition to organic farming; and in Vilanova de Bellpuig, organic production was developed. For each location and crop season, climatic (Table 1) and soil parameters (Table 2) were characterised. The crop used for all locations was processing tomato, Lycopersicon esculentum cv. Perfectpeel. Tomato plantlets were transplanted in the field, with1.5 m between rows and 20 cm between plants, resulting in an average crop density of 33 300 plants_ ha–1. Table 3 provides additional information on mulching, planting and final harvest dates, bed type, irrigation system and crop covering. Crops were irrigated with a single drip tapeline at the middle of the row. Irrigation management and the predominant weed population are described in Cirujeda *et al*. (2012).

Mulch materials tested

Seven agricultural mulch films were selected, representing all types of mulch materials (conventional, oxo-degradable and biodegradable plastics, and paper) in the market for use without regulatory restrictions in any production system (Table 4). The composition and manufacturer of each product are presented in Table 4. Two plastic mulches (Biofilm, BF; Mater-Bi, MB) and two paper biodegradable mulches (MimGreen, PMG; Saikraft, PSA), together with conventional lineal PE (negative control) were tested at all locations. An additional biodegradable plastic mulch (Bio-Flex, BFx) was tested at Catalunya and an oxo-degradable polyethylene mulch (Enviroplast, EvP) at Castilla-La Mancha, Aragón and Navarra. Mulches were generally opaque and black; only PSA paper mulch was light brown. All mulch rolls were 1.2m wide, except BF, which was 1.4 m. Laying of mulches was carried out mechanically between 2 May and 12 June (Table 3), leaving the central 0.8m exposed to the air, and 0.2–0.3m on both sides buried in the soil. For the biodegradable plastics (BF, MB and BFx), stretching tension at laying was reduced from that used for PE. PMG paper required a very low stretching tension and PSA was laid without tension, with a significant reduction of the operation speed.

Mulch degradation

After the final harvest of the tomato crop, plant tops were cut and removed. Mulch degradation was evaluated directly at the surface and into the soil, after manually removing the soil over the buried mulch area on both sides of the mulch. Degradation was assessed by selecting two parameters of a qualitative scale (Table 5) developed by Novamont S.p.A., Po di Tramontana (Italy) Research Centre and the University of Lleida (Spain) during 2000–02 (Guerrini 2003): above-soil degradation and in-soil degradation. No in-soil degradation was registered in 2006 for Valdegón. For above-soil degradation, the scale assigns a 1–9 score according to the mulch soil coverage (Table 5). An equivalent scale considering mulch dematerialisation was applied for the in-soil degradation of the buried area of the mulches (Table 5).

To facilitate the implementation of the qualitative scale for the five research groups, a preliminary visual scale was developed after the first year of the trials. This preliminary scale was prepared from some selected pictures (Figs 1, 2). The above-soil degradation pictures were selected to refer the scores of the qualitative scale to a linear scale according to the percentage of mulch-covered soil area: 1 (0%), 2 (12.5%), 3 (25%), 4 (38%), 5 (50%), 6 (63%), 7 (75%), 8 (88%), and 9 (100). An inverted linear scale (1, 100% dematerialised; 9, 0% dematerialised) was approximated for the in-soil degradation of the buried mulch area.

Generally, the scales were applied to assess the degradation of the mulch at the time the crop cycle ended (Table 3). Degradation rate was calculated as the average percentage of degradation per day, from the laying-on of mulching to the end of the crop cycle. The experimental design was randomized complete block design, with four replicates per location and year. Each block comprised 20-m-long rows of all treatments carried out at the corresponding location. Data were whole numbers, which required logarithmic function transformation

(Steel and Torrie 1980) to comply with the requirements of analysis of variance (ANOVA), which was carried out with the statistical package Statgraphics version 5.1 (Statpoint Technologies, Warrenton, VA, USA). Because preliminary ANOVAs revealed significant interactions between mulch material, location, and year, individual ANOVAs per location and year were carried out. When F was significant ($P < 0.05$), means were separated with corresponding l.s.d. tests at $P = 0.05$ confidence level.

Results and discussion

Above-soil degradation

Results show the sensitivity of the qualitative scale for identifying differences in the field degradation of mulching materials. The degradation scores of all locations and crop seasons together (Fig. 3) differentiate between the different families of mulches. Major degradation was found in BF (Fig. 1; score 2) followed by MB (Fig. 1; score 4) and paper mulches. The oxo-degradable EvP and the biodegradable BFx degraded less (Fig. 1; score 8) and PE did not degrade (Fig. 1; score 9). The differences in degradation were mainly due to the material (~50% of total variability). However, environment and agricultural practices together (i.e. location and crop season) were responsible for over one-third of the total variation. Despite this, only a few studies have compared mulch degradation in different crop seasons and locations (Hoshino *et al*. 2001; Shogren and Hochmuth 2004; Miles *et al*. 2012).

As expected, PE mulch remained stable in all circumstances (Fig. 3). Depending on the location and crop season, EvP (oxodegradable) mulch degraded to a different extent (Fig. 3); this is attributed to an environmental interaction with the triggering of the degradation process induced by the pro-oxidant additive

'Envirocare' (Bonora and De Corte 2003). Data on the UV radiation reaching the film, recognised as one of the main factors in EvP degradation, were not available; however, global radiation was lower in Almudévar–Montañana than in Cadreita or Ciudad Real (Table 1), and higher radiation did not involve higher degradation. The high EvP degradation in Almudévar–Montañana was associated with occasional but usually strong winds (Table 1) that damaged the mulch by enlarging previous tears. Meanwhile, in Ciudad Real and Cadreita, EvP degraded significantly more than PE in only one crop season each (Fig. 3). As reported by Kyrikou *et al*. (2011), EvP was observed to become very brittle, whereas this was not the case for PE, which retains its mechanical properties throughout the crop cycle (Martin-Closas *et al.* 2008). Mulch brittleness allows easier piercing of the mulch by weeds, which further favours enlargement of the breakings. This was the case at Montañana in 2008, where *Cyperus rotundus* weed grew (Cirujeda *et al*. 2012). As a result of the degradation dynamics, the above-soil degradation rate was 0.5% day–1 for PE and 2.5% day–1 for EvP (Fig. 4).

The BF and MB above-soil degradation was markedly different from that of PE and EvP. Biofilm, made with cereal flour, degraded most and fastest (Figs 3, 4), followed by MB, with thermoplastic starch. Degradation of BFx, with polylactic acid, was closer to PE. As for PE and EvP, solar radiation is among the main degradation factors for this family of materials containing the synthetic biodegradable polyester PBTA (Briassoulis 2006; Kijchavengkul *et al*. 2008), but rainfall and irrigation water are also relevant. Under Mediterranean continental climate, most rainfall occurs in late summer and autumn (end of the crop season); thus, radiation is the main environmental factor contributing to the initial degradation of the materials tested. Hence, the time that mulch remains unprotected from solar radiation, between mulching and transplanting and up to maximum crop coverage (Table 3), are determinants for the later mulch degradation. At Montañana in 2008, early rainfalls followed by a flood did not allow earlier transplanting after mulching, and consequently degradation of the mulches was increased (Fig. 3).

After the processing-tomato crop reaches maximum soil coverage, solar radiation ceases to be the main degradation factor and the creeping growth habit of plants presses the mulch against the soil, building up a humid environment, which favours degradation and biodegradation. This operated for BF and MB mulches but not for BFx, due to its PLA-based composition being more resistant to biodegradation (Figs 3, 4). Mostafa *et al*. (2010) reported MB to degrade faster than BFx. However, direct and continued contact of water from the irrigation tape with the film may result in PLA hydrolysis (Lucas *et al*. 2008), as it was locally evidenced for BFx.

Biodegradable plastic mulches may degrade faster than paper mulches under scant above-soil contact of mulch with water, as in Vilanova de Bellpuig and Almudévar/Montañana, with scarce rainfall and high radiation (Table 1, Fig. 4). However, although in Ciudad Real rainfall was also scarce, irrigation water wet the mulches. In Valdegón and Cadreita, rainfall was higher and the degradation rates of plastic and paper mulches were closer (Fig. 4).

Degradation was equivalent for both papers tested regardless of whether manufactured with new (PMG) or with recycled (PSA) cellulose fibres, and coated with black dye (PMG) or not coated (PSA) (Fig. 3). For paper mulches, humidity and wind are the main degradation factors. After a rainfall episode, the strength of the paper mulch in the edge-line between the in-soil and the above-soil mulch is significantly reduced and it will easily break; then wind will blow away the mulch. Higher rainfall at Cadreita and Valdegón (Table 1) than at Vilanova de Bellpuig and Almudévar/Montañana was responsible for the greater degradation and higher degradation rates (Figs 3, 4) of the paper mulches at the former locations. Not only does rainfall affect degradation and breaking of the paper; irrigation water reaching the buried area (Ciudad Real in 2006, Valdegón in 2008) facilitates the breaking in the borderline between in-soil and above-soil mulch, which may be followed by the mulch being blown up before becoming protected and held by the crop coverage. The abrasive sandy soils of Ciudad Real, in 2006, and Valdegón in 2008, (Table 2) facilitated the breaking in the lateral edges. Weeds were unable to pierce and grow through the paper mulches (Shogren and Hochmuth 2004; Cirujeda *et al*. 2012), and so paper mulches provide very good protection against them (Cirujeda *et al*. 2012), although some persistent weeds (*Cyperus rotundus*) growing below the mulch pressed it upwards and created some stress in the lateral edge. However, the use of these mulches in rainy and windy locations is limited. Degradation of paper mulches in contact with moisture could be slowed by curing the paper mulch with vegetable oils (Shogren 1999; Shogren and Hochmuth 2004), latex, or biodegradable polymers (Brault *et al*. 2002). Above-soil degradation rates for paper mulches were 3.2% day–1 and 3.1% day–1 for PMG and PSA, respectively (Fig. 4).

In-soil degradation

As was the case for above-soil degradation, in-soil degradation differentiated among the different families of mulches. Over 65% of the variability in the in-soil degradation was due to the material effect. The more stable in-soil than above-soil environments are presumably associated with the lower variation linked to location or season (~10% each). Paper mulches, together with BF, degraded most (Fig. 2; scores 2 and 3, respectively) and fastest in the majority of in-soil environments, followed by less degradation of MB mulches (Fig. 2; score 4) (Figs 5, 6). No significant degradation difference was identified between BFx and EvP and the stable PE mulch

(Fig. 2; score 9) (Fig. 5), with scarce occasional breakings in the three mulches attributed to the lateral pressure exerted by the tractor wheels at mulching or during mechanical weeding between crop lines. As mentioned above, degradation induced by Envirocare in oxo-degradable plastics (i.e. EvP) is highly dependent on UV-radiation exposure, but it is also triggered by temperatures close to those of composting environments

(50_708C) (Bonora and De Corte 2003; Jakubowicz 2003), unusual in agricultural soils. Consequently, as in recent soilburial tests (Briassoulis *et al*. 2015; Selke *et al*. 2015), no degradation of EvP in-soil was identified under the environments tested.

Humidity and microbiota activity (which relies on soil humidity, temperature and organic matter content) are the main degradation factors for in-soil degradation. Temperatures at the buried areas of the mulches were similar among all locations and suitable for soil biological activity (data not shown). Organic matter levels were high at Vilanova de Bellpuig and medium at all other locations (Table 2). Thus, soil humidity remained the main limiting factor for in-soil biodegradation.

When soil moisture supports soil biological activity, the in-soil mulch degradation rate is expected to be high. At Ciudad Real, the irrigation system wetting the buried mulch areas facilitated soil biological activity, which prompted degradation of most mulches (Fig. 6). At Cadreita and Valdegón, rainfall moistening the soil allowed degradation. However, at Vilanova de Bellpuig, with high organic matter content, the lower degradation scores, especially for paper mulches (Fig. 6) in 2006 and 2007, were very likely the result of limited soil biological activity under the extremely scarce rainfall. Apart from Vilanova de Bellpuig, average degradation rates were highest for paper and BF mulches (5.4–6.2% day–1) and for MB (4% day–1), and lowest for EvP (0.73% day–1) and BFx (0.73% day–1), tested only at Vilanova de Bellpuig (Fig. 6). Results obtained with the qualitative scale were in accord with other findings under laboratory and field conditions (Mostafa *et al*. 2010; Saadi *et al*. 2012, 2013).

Qualitative scale

The need for a standardised methodology to evaluate field degradation of degradable mulches resulted in a first qualitative scale (Table 5). Another qualitative scale for paper mulches (Shogren and Hochmuth 2004) relies on five visual scores. Miles *et al*. (2012) suggested number of rips, tears and holes (RTHs) and visual deterioration percentage (PVD) for abovesoil mulch degradation.

A unified qualitative degradation scale aims to assess the mulch degradation regardless of the material and final mulch product (plastic film, paper sheet, nonwoven, hydro-mulch, etc.). It should easily describe above- and in-soil mulch degradation, without specific technology or intensive labour. In addition, it should directly address the mulch functionality for the crop. The above-soil mulch functionality depends on its soil coverage; thus, soil coverage is convenient for the evaluation (Guerrini 2003; Miles *et al*. 2012) and proved useful (Martín-Closas and Pelacho 2004; Caprara *et al*. 2006; Miles *et al*. 2012). Guerrini (2003) applied soil coverage in a downwards scale from 100% (score 9) to 0% soil coverage (score 1). By contrast, Miles *et al*. (2012) applied upward percentages, from 0% (intact film) to 100% (fully degraded). Both methods allow a good evaluation of soil coverage by the mulch. We consider that for a field qualitative scale, scores representing percentage intervals provide sufficient accuracy and are easier to apply than specific percentages. The visual photographic guide (Figs 1 and 2) proved very useful to unify criteria among different users.

All three mentioned scales evaluate the above-soil mulch damages. Damages do not decrease soil coverage but are the first signs of mulch degradation and involve changes in the mulch functionality. Compared with established scores for describing damage (Table 5), the Miles *et al*. (2012) RTH proposal is very specific and provides a step forward in facilitating evaluation. Early RTHs may reveal, among others, a deficient converting process of the material, or perforation by hail, whereas paper mulch transversal tears are frequently associated with excessive tensile forces during laying or with changes in the contraction–expansion of the paper.

Manual evaluation of mulch strength (Table 5) can be useful when considering early effects of environmental parameters on mulch properties. This evaluation may be achieved by comparing the mulch to be tested with an unweathered sample.

Guerrini (2003) and Shogren and Hochmuth (2004) estimated the film or sheet persistence in the buried area. The Shogren and Hochmuth (2004) scale establishes 'nearly 50% or 100% of tuck area degraded'; however, the present work reveals that more accurate determination of this parameter is useful. On the other hand, the Shogren and Hochmuth (2004) scale incorporates 'mulch on top of bed detached from tuck area', which is relevant for the mulch persistence. We suggest considering this damage as included in RTHs. A photographic monitoring of the time-course degradation is highly recommended.

After analysing all of the above-mentioned factors, we propose a unified qualitative scale (Table 6) recommended to be used every 2 weeks. In the present study, results from the end of the crop cycle have been shown. Use of qualitative scales along the crop cycle is found in the literature (Shogren and Hochmuth 2004; Caprara *et al*. 2006; Martin-Closas *et al*. 2008; Filippi *et al*. 2011; Miles *et al*. 2012; Cowan *et al*. 2013).

In order to improve understanding of results obtained with the qualitative scale, basic soil analysis and environmental parameter registration is advisable: daily air and soil (buried area) temperatures, air humidity, soil water content, rainfall and solar UV radiation. Agronomic practices that affect the mulch material must also be considered. Finally, the crop structure and development will affect the mulch degradation pattern;

thus, including mulch plots without crop will provide controls for degradation that will enable comparisons among crops and among environments.

Conclusions

Degradation in the field of different mulch materials, in a processing-tomato crop, has been characterised through a formerly designed qualitative scale, which has been improved in this work by a visual rating guide. Results showed different degradation trends depending on the nature of the materials. Biodegradable plastic BFx and oxo-degradable polyethylene, EvP, showed the lowest above-soil degradation, followed by the paper mulches and the biodegradable plastics, MB and then BF, which was the most degraded. Above-soil daily degradation rate was high for BF, MB and paper mulches, PMG and PSA, and lowest for EvP and BFx. In-soil degradation was high and equivalent among PMG, PSA and BF, medium for MB, and low for BFx and EvP. In-soil daily degradation rates were high for PMG, PSA and BF, medium for MB, and low for BFx and EvP. Results were influenced by environmental factors, but also by agricultural practices. The qualitative scale applied proved efficient and useful for determining degradation, but based on the experience of this work, together with that of other authors, we propose a unified qualitative degradation scale.

Acknowledgements

The authors thank the Spanish Ministry of Science and Education, MEC (Research Project INIA RTA2005-00189-C05) and the University of Lleida, Spain (Research Project UdL006197) for financial support. We also thank Novamont S.p.A., Saica SA, MimCord SA, Fkur GmbHOerlemans Plastics and Genplast SA for providing the mulch materials.

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Table 1. Climatic parameters during the three tomato crop seasons in the five locations

MT, MTmax, MTmin: Mean, mean maximum, mean minimum air temperature (8C); MRh, mean relative humidity (%); MW, MWmax: mean, mean maximum wind speed ($m\,s^{-1}$); Rain, total rainfall (mm); G.Ra, global radiation ($MJ\,m^{-2}$)

Location	Season	MT	MTmax	MTmin	MRh	MW	MWmax	Rain	G.
Cadreita	200	21.3	29.	14.	61	2	7.8	1	31
	200	19.8	26.	13.	61	2	8.0	66	32
	200	19.2	26.	12.	67	2	7.0	1	31
Valdegón	200	20.3	27.	13.	59	2	8.3	1	29
	200	19.1	26.	12.	60	2	8.0	1	26
	200	18.9	26.	12.	63	1	7.7	3	26
Almudévar	200	23.0	29.	14.	53	2	13.0	170	29
	200	21.1	28.	13.	54	2	12.7	58	26
Montañana	200	22.1	29.	15.	59	1	15.8	32	21
Ciudad Real	200	23.9	32.	14.	39	1	7.3	55	32
	200	21.7	30.	12.	47	1	6.6	80	27
	200	22.1	30.	12.	44	1	7.0	23	30
Vilanova de	200	22.3	30.	14.	53	0	6.8	24	28
	200	21.7	29.	14.	56	0	6.5	26	26
	200	21.8	29.	14.	62	0	5.9	1	24

Table 2. Soil characterisation during the three tomato crop seasons at the five locations

OM, Organic matter (%); EC, electrical conductivity ($dS\,m^{-1}$); N, total N-NO_3 (Cadreita, total N); P, total phosphorus; K, total potassium (all $mg\,kg^{-1}$); $CaCO_3$, equivalent calcium carbonate (%); Si-CL, silty clay loam; Si-C, silty clay; Si-L, silty loam; Sa-L, sandy loam; CL, clay loam; Sa-CL, sandy clay loam; L, loam

Location	Year	Soil horizon (cm)	OM	pH	Texture	EC	N	P	K	$CaCO_3$
Cadreita	2006	0–20	2.03	8	Si-CL	1.08	1570	6	1	31
	2007	0–20	2.24	8	Si-CL	1.06	1575	6	2	34
	2008	0–20	1.75	8	Si-	1.04	260	6	1	32
Valdegón	2006	0–30	2.00	8	Si-CL	0.26	171	4	5	34
	2007	0–30	1.56	8	Si-CL	0.31	165	1	4	36
	2008	0–40	0.84	8	Sa-	0.12	23	4	1	24
Almudévar	2006	0–20	2.63	8	Si-CL	1.52	–	1	2	11
	2007	0–20	–	–	Si-CL	–	–	–	–	–
Montañana	2008	0–20	2.79	8	CL	0.27	23	1	3	–
Ciudad Real	2006	0–25	1.85	8	Sa-CL	0.58	20	5	3	27
	2007	0–35	2.20	8	L	0.22	29	4	4	36
	2008	0–25	2.00	7	L	0.37	22	5	1	8
Vilanova de	2006	0–20	3.41	8	Si-	1.09	93	5	7	25
	2007	0–20	4.14	8	Si-CL	0.49	24	4	6	33
	2008	0–20	3.65	8	Si-	0.43	46	5	6	43

Table 3. Mulching, planting and final harvest dates, days to degradation control, bed type, irrigation system, and degree of crop covering of the tomato cropping system

bm, Drip-line below mulch; b, drip line buried in soil. For crop cover: total, crop totally covers the mulch bed; partial: crop partially covers the mulch bed

Location	Year	Altitude (m)	Mulching date	Planting date	Harvest	Days to control	Bed type	Drip system	Crop cover
Cadreita	2006	288	18 May	24 May	11 Sept.	130	Raised	bm-b	Total
	2007	288	11 May	29 May	21 Sept.	139	Raised	bm-b	Total
	2008	288	09 May	12 May	25 Sept.	137	Raised	bm-b	Total
Valdegón	2006	346	02 May	10 May	02 Sept.	124	Raised	bm-b	Total
	2007	346	08 May	11 May	05 Sept.	121	Raised	bm-b	Total
	2008	346	07 May	13 May	08 Sept.	125	Raised	bm-b	Total
Almudévar	2006	456	22 May	25 May	18 Sept.	119	Raised	bm	Partial
	2007	456	01 June	04 June	18 Sept.	109	Raised	bm	Total
Montañana	2008	218	22 May	19 June	07 Oct.	138	Raised	bm	Total
Ciudad Real	2006	640	17 May	18 May	14 Sept.	120	Flat	bm	Total
	2007	640	16 May	18 May	03 Sept.	102	Flat	bm	Total
	2008	640	27 May	04 June	17 Sept.	113	Flat	bm	Total
Vilanova de Bellpuig	2006	261	06 May	08 May	18 Aug.	105	Flat	bm	Partial
	2007	261	28 May	30 May	20 Sept.	116	Flat	bm-b	Partial
	2008	261	12 June	13 June	07 Oct.	118	Flat	bm-b	Partial

Table 4. Product name, composition, manufacturer and thickness of the selected mulch films

Product name	Main composition	Manufacturer	Thickness–grammage
Biofilm® (BF)	Whole seed wheat-corn flour, co-polyester	Limagrain/Barbier	17 mm
Bio-Flex® (BFx)	Polylactic acid, co-polyester	Fkur Kunststoff GmbH/ Oerlemans Plastics	15 mm
Mater-Bi® NF803 (MB)	Corn thermoplastic starch, co-polyester, vegetable oils	Novamont S.p.A.	15 mm
MimGreen® Paper (PMG)	Virgin cellulosic fibre with black dye in upper side	MimCord SA	85 g m^{-2}
Saikraft® Paper (PSA)	Recycled cellulosic fibre	Saica SA	140 g m^{-2}
Enviroplast® (EvP)	Oxo-polyethylene with Envirocare® additive	Genplast SA	15 mm
Polyethylene (PE)	Lineal low density polyethylene	Solplast SA	15 mm

Table 5. Qualitative scale for the evaluation of the above-soil and in-soil degradation of mulch films for field crop trials (Guerrini 2003)

Parameter	Criteria	Score
Above-soil degradation	Soil coverage (%)	1, 0% coverage; 9, 100% coverage
In-soil degradation	Dematerialisation (%)	1, 100% dematerialised; 9, intact mulch
Damages	Number	1, Large no. of damages; 9, no damage
Strength	Resistance to tear	1, No elasticity, extremely brittle; 9, full elasticity, no brittle

Table 6. Unified qualitative scale for the field evaluation of degradable mulch

Parameter	Criteria	Units/scores
	Above-soil qualitative evaluation	
Soil coverage by mulch	Area of soil covered by mulch material	Scores from 9 to 1: 9, 100% soil covered; 5, 50% soil covered; 1, 0% soil covered
Damages in mulch area	No. of lesions (rips, tears and holes; RTH)	Number of lesions per area (RTH m^{-2})
Damages in the edge line (interface air-soil)	Length of detached mulch	Detached length in the edge line per length of row ($m\ m^{-1}$)
Strength	Resistance to tear	9, 100% full elasticity ;5, 50% full elasticity; 1, 0% extremely brittle
	In-soil qualitative evaluation	
In-soil mulch dematerialization	% Mulch presence	9, Intact mulch; 5, 50% mulch; 1, mulch totally absent

Fig. 1. Visual qualitative scale for field evaluation of the above-soil mulch degradation. Left to right in upper row: scores 1, 2 (BF) and 3; in middle row: scores 4 (MB), 5 and 6; in lower row: scores 7, 8 (BFx) and 9 (PE). Degradation scores rank from 1 (0% coverage) to 9 (100% coverage).

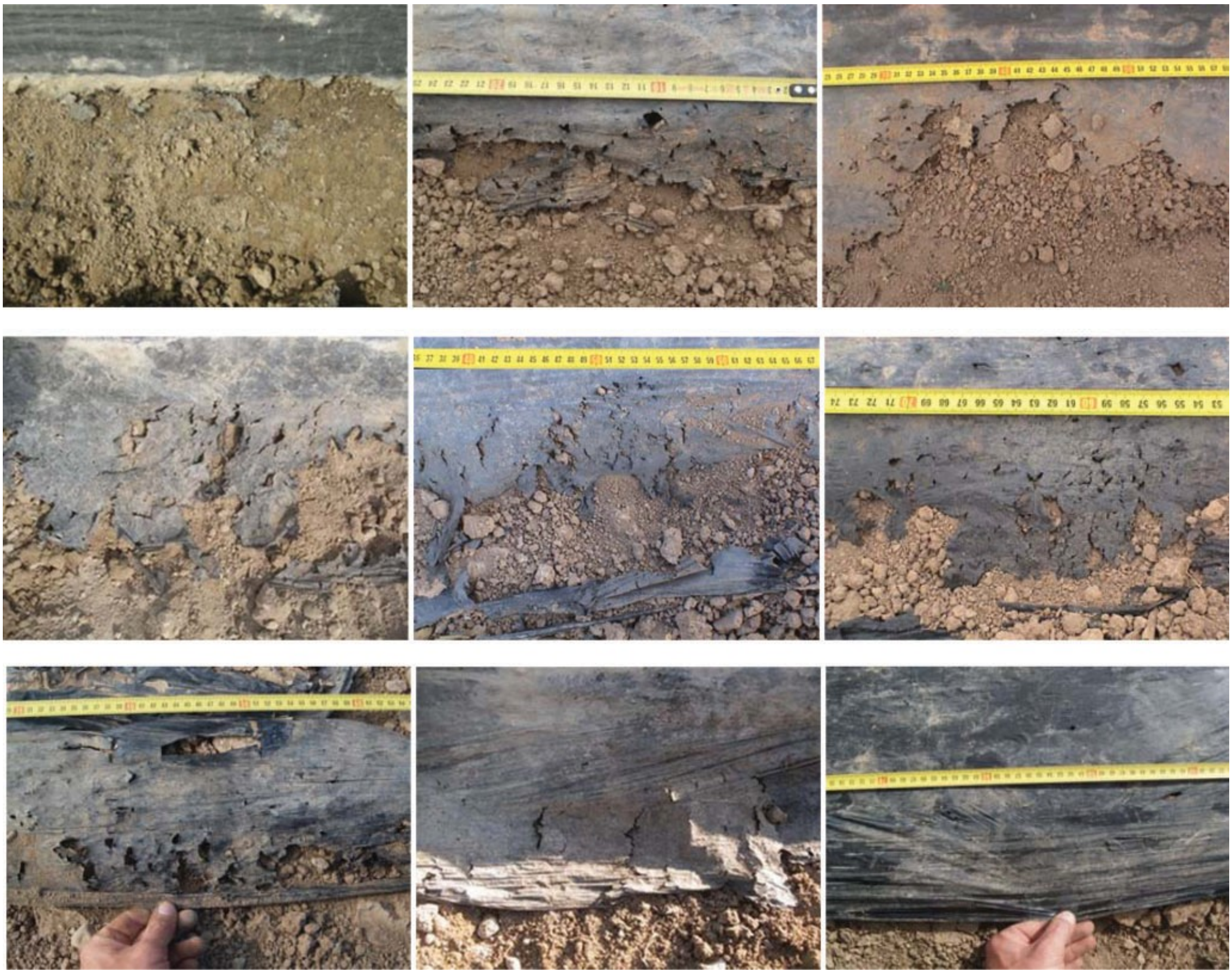

Fig. 2. Visual qualitative scale for field evaluation of the in-soil mulch degradation. Left to right in upper row: scores 1 (PMG), 2 (BF) and 3 (PMG); in middle row: scores 4 (MB), 5 and 6; in lower row: scores 7, 8 and 9 (PE). Degradation scores rank from 1 (100% dematerialised) to 9 (intact mulch).

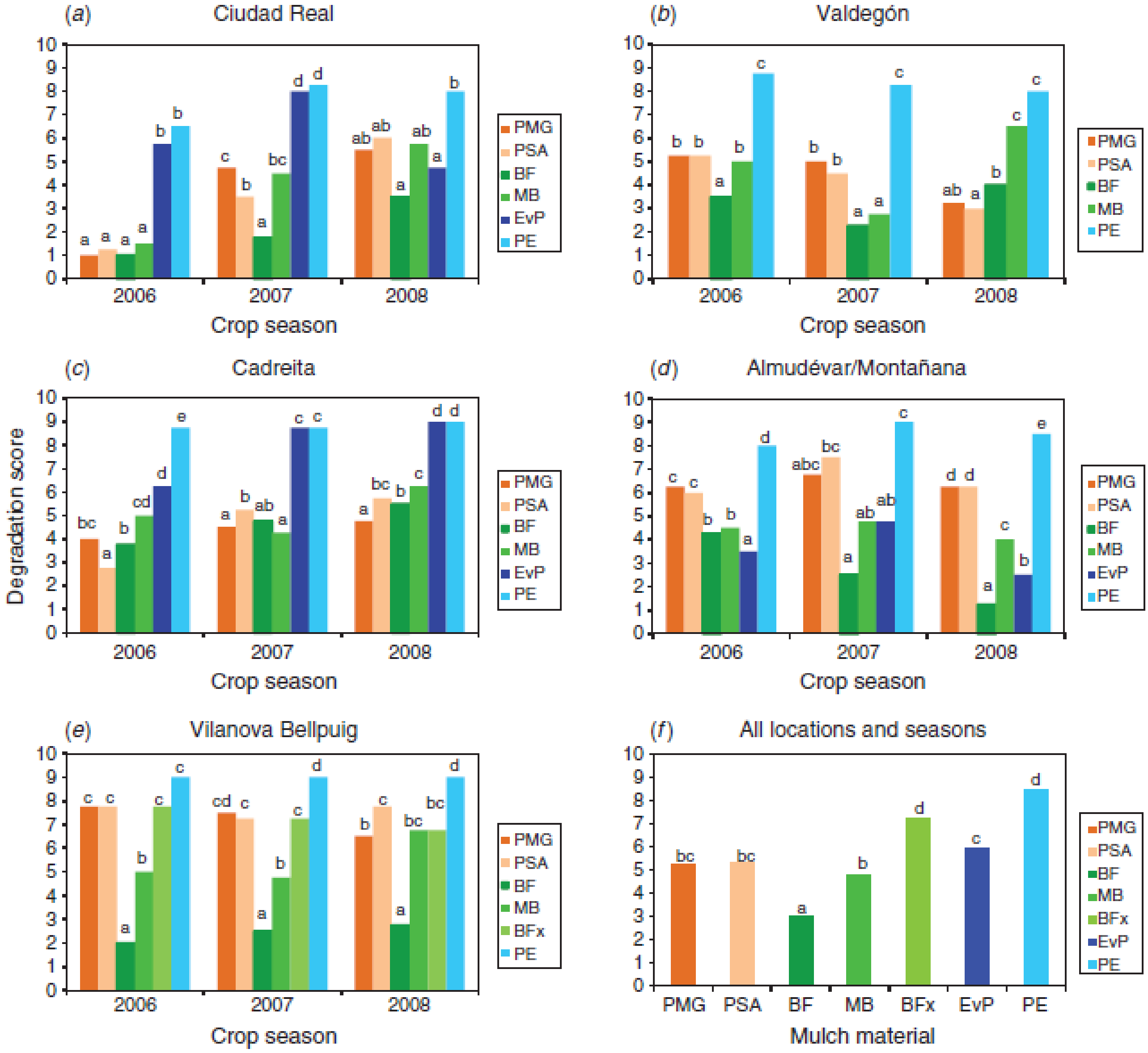

Fig. 3. Above-soil mulch degradation according to the end score from the qualitative scale (1, 0% soil coverage to 9, 100% soil coverage) (*a*–*e*) in the five locations and (*f*) for all locations and crop seasons together. For every location and year, and for all locations and seasons together, means with the same letter are not significantly different at $P = 0.05$.

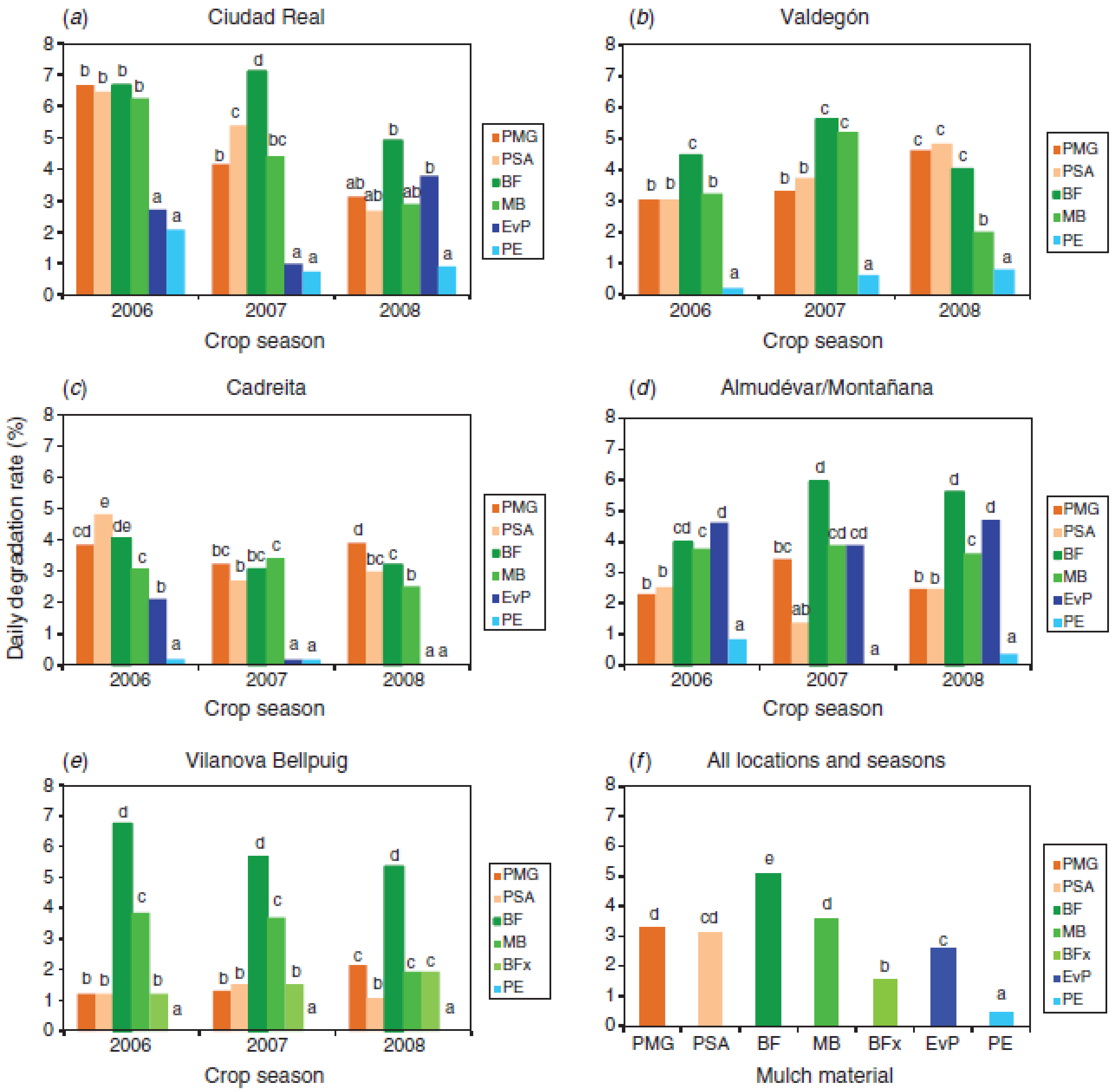

Fig. 4. Daily above-soil mulch degradation rate according to the end score from the qualitative scale (1, 0% soil coverage to 9, 100% soil coverage) and to the crop season (*a*–*e*) in the five locations and (*f*) for all locations and crop seasons together. For every location and year, and for all locations and seasons together, means with the same letter are not significantly different at $P = 0.05$.

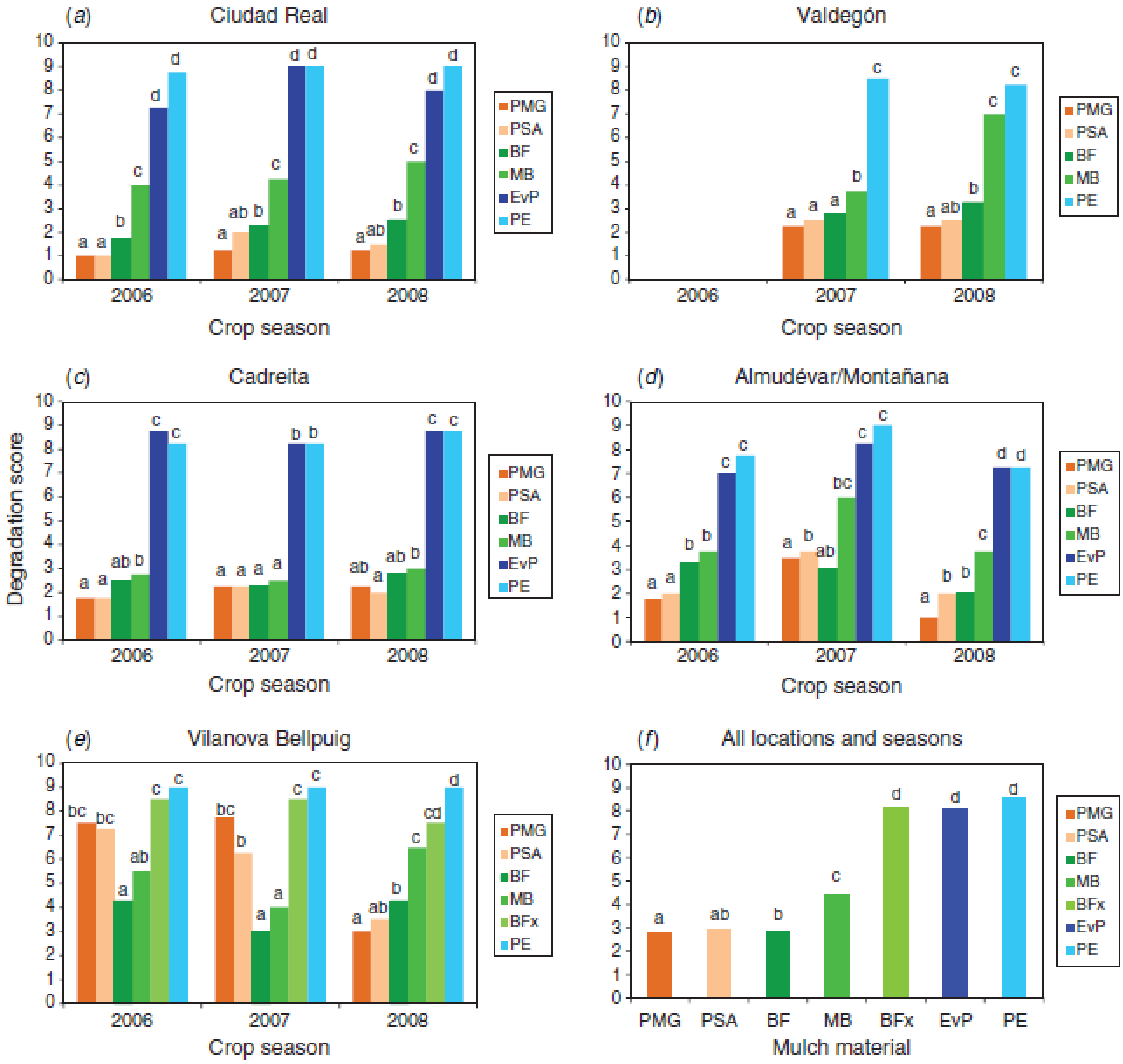

Fig. 5. In-soil mulch degradation according to the end score from the qualitative scale (1, 0% soil coverage to 9, 100% soil coverage) (*a–e*) in the five locations and (*f*) for all locations and crop seasons together. For every location and year, and for all locations and seasons together, means with the same letter are not significantly different at $P = 0.05$.

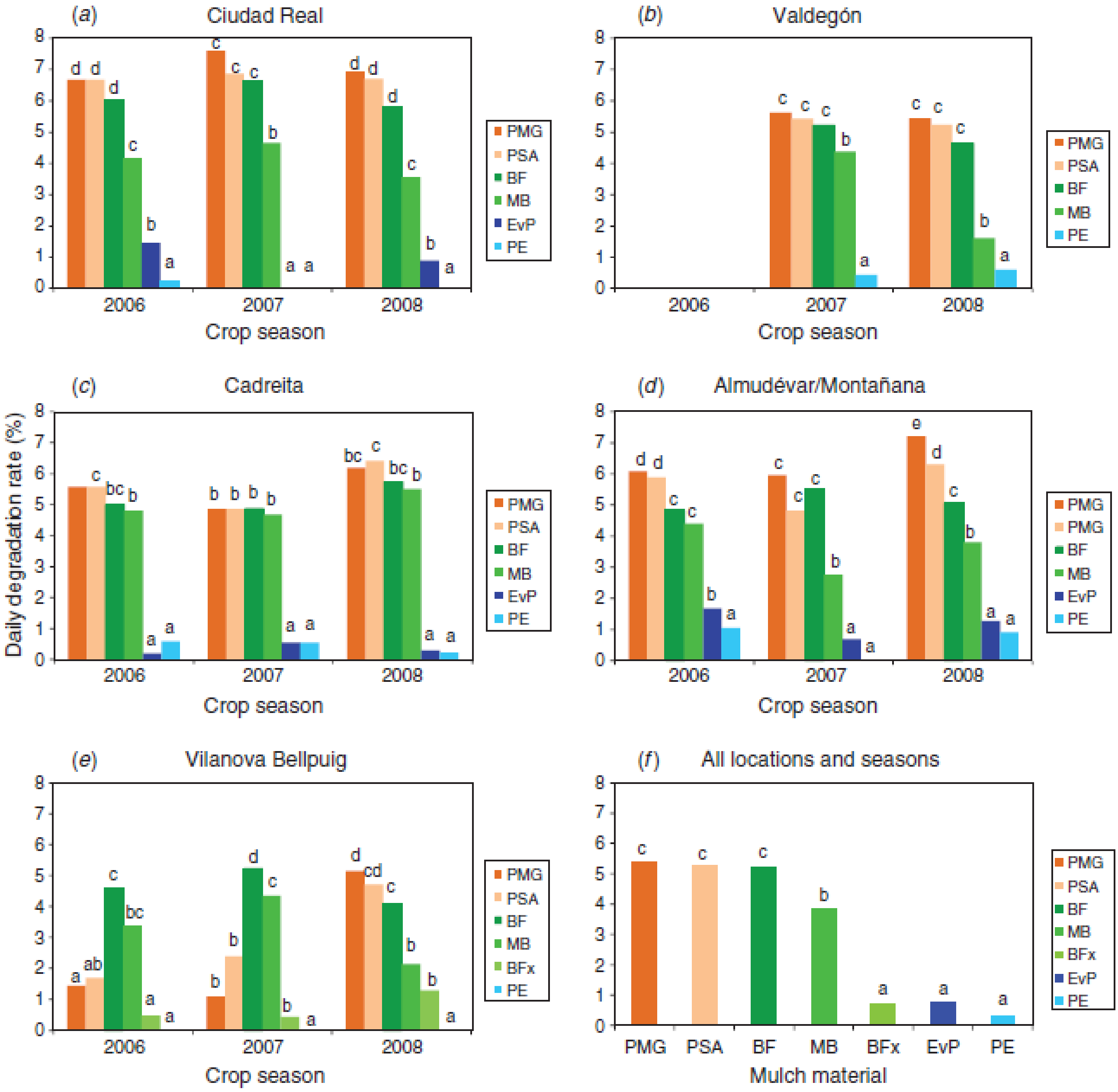

Fig. 6. Daily in-soil mulch degradation rate according to the end score from the qualitative scale (1, 0% soil coverage to 9, 100% soil coverage) and to the crop season (*a–e*) in the five locations and (*f*) for all locations and crop seasons together. For every location and year, and for all locations and seasons together, means with the same letter are not significantly different at $P = 0.05$.